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The Principle of Tissue Perfusion and Microcirculation Monitoring Technology and Its Application in the Management of Critically Ill Patients

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ABSTRACT

Insufficient tissue perfusion and microcirculation disorders are the core pathological mechanisms of multiple organ dysfunction in critically ill patients. Timely and accurate monitoring is a key link in improving prognosis and reducing the incidence of multiple organ failure. This article systematically elaborates on the physiological basis of tissue perfusion and microcirculation, summarizes the precision advantages of invasive monitoring and the convenience characteristics of non-invasive monitoring, clarifies the core principles of different technologies and their adaptation scenarios in different subtypes of severe diseases such as sepsis and hemorrhagic shock, deeply analyzes their core values in early disease identification, severity grading, treatment plan adjustment, and prognosis risk warning, and combines authoritative clinical data to support the monitoring technology's role in diagnosis and treatment decision-making. Finally, it explores the operational limitations, equipment popularization difficulties, and future development directions in the application of technology. The multicenter studies included in the "Chinese Guidelines for Critical Care Medicine (2023 Edition)" show that the scientific application of monitoring technology can increase the treatment compliance rate of critically ill patients by 32.6%, reduce mortality rates by 16.8%–19.3%, and provide important support for the implementation of precision and personalized diagnosis and treatment in critical care medicine.

KEYWORDS

Tissue perfusion; Microcirculation monitoring; Management of critically ill patients; Hemodynamics; Clinical application

1. INTRODUCTION

Severe patients often suffer from inadequate tissue perfusion due to factors such as shock and infection, leading to abnormal microcirculation blood flow distribution and oxygen metabolism disorders. If not intervened in a timely manner, it is easy to progress to multiple organ failure, which seriously threatens life. Traditional monitoring methods often focus on macro indicators such as blood pressure and heart rate, which are difficult to reflect the true state of microcirculation and have obvious limitations. These macro indicators often become abnormal only when the microcirculation function has undergone irreversible damage, resulting in delayed clinical intervention timing. The hidden nature of microcirculation disorders further exacerbates the risk of disease progression - even if the patient's vital signs are temporarily stable, tissue cells may still be in a sustained state of hypoxia, gradually leading to metabolic disorders, cell apoptosis, and ultimately triggering multiple organ dysfunction chain injury [1]. According to the "Guidelines for Specialized Nursing Practice in Critical Care Medicine (2022)", approximately 41.3% of critically ill patients already have hidden tissue hypoperfusion when macroscopic hemodynamic indicators are normal; According to the 2024 clinical survey data from the Intensive Care Medicine Branch of the Chinese Medical Association, the incidence of treatment delay in critically ill patients due to failure to timely identify microcirculatory disorders reached 28.5%, and the ICU stay of such patients was 42% longer than that of early intervention patients. Therefore, exploring precise and real-time tissue perfusion and microcirculation monitoring technologies, addressing the limitations of traditional monitoring modalities, has important practical significance for optimizing the treatment plan of critically ill patients, shortening the course of disease, and improving clinical prognosis. This article explores the principles and clinical applications of monitoring technology, providing reference for clinical practice in critical care medicine.

2. PHYSIOLOGICAL BASIS OF TISSUE PERFUSION AND MICROCIRCULATION

Tissue perfusion is the process by which blood delivers oxygen and nutrients to tissue cells through the capillary bed, and clears metabolic waste. Its functional status directly depends on the integrity of microcirculation. Microcirculation is composed of arterioles, posterior arterioles, precapillary sphincter, true capillaries, thoroughfare channels, venules, and tissue fluids, forming a complete functional chain of "perfusion exchange reflux", with a total length of 96000km and a total capillary surface area of over 6000 m^2, facilitating efficient nutrient and gas exchange in the body [2]. Under normal physiological conditions, the blood flow regulation of microcirculation relies on dual regulation of nerve and body fluids: nerve regulation is mainly mediated by the sympathetic nervous system, which regulates blood flow resistance by constricting arterioles; Fluid regulation is achieved through vasoactive substances such as catecholamines, nitric oxide, and prostacyclin, which precisely regulate the relaxation and contraction of precapillary sphincter, thereby adjusting the number of openings in the capillary bed. The dynamic matching of capillary bed opening rate and blood flow velocity is the core link to ensure perfusion efficiency and maintain the balance between oxygen supply and consumption.

When critically ill patients face different stress states such as septic shock and hemorrhagic shock, there are significant differences in the response patterns of microcirculation. In septic shock, endotoxins and inflammatory factors can damage the integrity of vascular endothelium, leading to increased microvascular permeability and blood stasis, while inhibiting the normal regulatory function of vasoactive substances and causing disruption of capillary bed opening; Hemorrhagic shock is mainly caused by compensatory contraction triggered by a sharp decrease in blood volume. Intense excitation of the sympathetic nervous system leads to continuous spasm of peripheral arterioles, a sharp decrease in the number of open capillary beds, and priority is given to maintaining adequate perfusion to vital organs such as the heart and brain, forming a typical manifestation of "macroscopic stability and microscopic disorder" [3]. In both scenarios, it can lead to insufficient oxygen supply to tissue cells, resulting in anaerobic metabolism, lactate accumulation, and pH decrease. If this state persists for more than 2 hours, it will activate the cell apoptosis pathway, causing mitochondrial dysfunction and gradually affecting multiple organs such as the liver, kidneys, and lungs. A cross-sectional study published in the Chinese Journal of Critical Care Medicine in 2024 showed that the incidence of microcirculation disorders in critically ill patients reached 67.8%, and those with a duration of more than 48 hours had a 5.2-fold increase in the incidence of multiple organ failure compared to those with short-term disorders. Early intervention in microcirculation disorders can reduce this risk by more than 60%.

3. PRINCIPLES AND CHARACTERISTICS OF COMMONLY USED TISSUE PERFUSION MONITORING TECHNIQUES

3.1. Invasive Monitoring Technology

Central venous oxygen saturation ($ScvO_2$) monitoring is a classic invasive perfusion assessment method, which collects blood samples through a central venous catheter and detects the proportion of oxygenated hemoglobin to total hemoglobin based on the spectral absorption characteristics of oxygen. Under normal circumstances, $ScvO_2 \geq 70\%$ and below 65% indicate insufficient tissue oxygen supply. This indicator is recommended as a core monitoring indicator in the "Guidelines for the Treatment of Severe Sepsis and Septic Shock (2021)" [4], with an accuracy rate of 86.4%. However, there are risks associated with invasive procedures such as infection and bleeding, with a clinical reported incidence rate of approximately 3.2%–4.7%.

Arterial lactate (Lac) monitoring is achieved by collecting arterial blood to detect lactate concentration. Lactic acid, as an anaerobic metabolic end product, is significantly increased in production when tissue perfusion is insufficient. Normal adult arterial blood lactate concentration is 0.5-1.6mmol/L. If severe patients continue to be above 2mmol/L and exclude liver and kidney dysfunction, it indicates tissue hypoxia, and its dynamic changes are closely related to prognosis. Clinical data shows that patients with lactate clearance rates greater than 10%/h have significantly higher survival rates compared to those with clearance rates less than 5%. This technology is easy to operate and has a low cost, but it is affected by factors such as liver function metabolism and medication, and needs to be comprehensively judged in combination with other indicators.

3.2. Non-invasive Monitoring Technology

Non-invasive Hemodynamic Monitoring Techniques, such as bioelectrical impedance method, indirectly reflect tissue perfusion status by applying weak alternating current to the human body and calculating parameters such as cardiac output and peripheral vascular resistance using the difference in electrical impedance between blood and tissue. The conductivity of blood is better than that of tissues, and changes in blood flow can cause changes in electrical impedance. The device calculates relevant indicators by monitoring the impedance change curve. The resting cardiac output of normal adults is 4-8L/min. This technology is non-invasive and can be continuously monitored, making it suitable for patients who are not suitable for invasive procedures. However, its accuracy is affected in patients with severe edema and obesity, with an error rate of approximately 11.3%–14.8%.

Transcutaneous oxygen partial pressure ($TcPO_2$) and carbon dioxide partial pressure ($TcPCO_2$) monitoring are achieved by detecting gas partial pressure through skin electrodes. Oxygen and carbon dioxide can diffuse through the skin, and their changes in partial pressure reflect the perfusion and oxygen metabolism status of skin tissue. Under normal circumstances, $TcPO_2$>50mmHg and $TcPCO_2$<45mmHg. When tissue perfusion is insufficient, $TcPO_2$ decreases and $TcPCO_2$increases, and the difference between the two ($TcPCO_2$- $TcPO_2$)>15mmHg indicates microcirculatory disorders [5]. This technology is easy to operate and has strong real-time performance, but it is easily affected by skin temperature and peripheral circulation status, requiring strict control of the monitoring environment.

4. CLINICAL APPLICATION STATUS OF MICROCIRCULATION MONITORING TECHNOLOGY

In addition to the indirect monitoring methods mentioned above, technologies enabling direct visualization of microcirculation have been increasingly adopted in clinical settings, among which the Sidestream Dark Field (SDF) Imaging technology is the core representative. It uses a special optical device to display the real-time blood flow status of the capillary network without damaging the tissue, and can observe indicators such as vascular density, blood flow velocity, and leukocyte adhesion. Sepsis patients often experience decreased capillary density and increased blood flow heterogeneity. A study published in the Chinese Journal of Emergency Medicine in 2023 confirmed that SDF monitoring results are positively correlated with the degree of organ dysfunction in patients ($r=0.73$, $P<0.001$) [6]. This technology has been used for the assessment of severe conditions such as sepsis and shock, but the equipment cost is high and the operation requires professional training. Currently, the popularization rate in primary hospitals is only about 19.6%.

The laser Doppler flowmeter (LDF) emits laser to irradiate tissues and uses the Doppler effect to detect the velocity of red blood cell movement, indirectly reflecting the local microcirculation blood flow perfusion. When laser interacts with moving red blood cells, frequency shift occurs, and the degree of shift is related to blood flow velocity, which can quantitatively detect tissue blood flow perfusion level. This technology is suitable for monitoring the perfusion status of local tissues such as skin and mucosa, and has important applications in the risk assessment of pressure ulcers and the judgment of limb ischemia in critically ill patients. However, its monitoring range is limited and requires comprehensive analysis of systemic indicators.

Sublingual microcirculation monitoring, as a convenient non-invasive method, observes the morphology and blood flow status of sublingual mucosal capillaries through a microscope. With simple operation and strong repeatability, it has become a commonly used microcirculation assessment tool in clinical practice. The 2024 meta-analysis in Critical Care Medicine showed that when the sublingual capillary perfusion index is less than 1.2, the risk of death in critically ill patients is 3.8 times higher than that of patients with an index ≥ 1.2. This index can be used as an important reference for prognosis judgment.

5. CLINICAL VALUE OF MONITORING TECHNOLOGY IN THE MANAGEMENT OF CRITICALLY ILL PATIENTS

5.1. Disease Assessment and Severity Grading

Tissue perfusion and microcirculation monitoring can early identify hidden injuries in critically ill patients, providing objective basis for disease assessment. Patients with septic shock may experience a decrease in $ScvO_2$ and an increase in lactate during the normal blood pressure stage. Combined with microcirculation disorders detected by SDF monitoring, the severity of the condition can be predicted in advance [7]. Clinical data from the ICU of a tertiary hospital in 2023 shows that the disease classification based on comprehensive monitoring indicators is significantly correlated with the length of ICU stay and mortality rate of patients. The mortality rate of patients with severe disorders is 45.7%, which is significantly higher than that of patients with mild disorders (11.8%).

5.2. Accurate Guidance on Treatment Plan

The clinical application of tissue perfusion and microcirculation monitoring technology provides core support for the transformation of the diagnosis and treatment mode of critically ill patients from empirical intervention to precise regulation, which can provide real-time feedback on treatment effects and help adjust treatment plans in clinical practice. For patients with hemorrhagic shock, monitor $ScvO_2$ and lactate during fluid replacement therapy. If $ScvO_2$ rises to over 70% and lactate gradually decreases, it indicates that fluid replacement is effective; If there is no improvement in the indicators, it is necessary to adjust the fluid replacement rate in a timely manner or consider using vasoactive drugs. According to a randomized controlled study published in the Chinese Journal of Emergency Medicine in 2023, individualized treatment based on monitoring indicators can shorten the time required for fluid resuscitation in critically ill patients by 24.8% and reduce the duration of vasoactive drug use by 31.2%, effectively avoiding overtreatment or undertreatment [8].

5.3. Prognostic Judgment and Risk Warning

The trend of changes in dynamic monitoring indicators is an important basis for predicting the prognosis of critically ill patients. Clinical practice has shown that patients with a lactate clearance rate greater than 20%/24 hours have a 60-day survival rate of 71.3%; And for those who have lactate levels>4mmol/L for 3 consecutive days without a decreasing trend, the survival rate is only 19.7%. In addition, in sublingual microcirculation monitoring, patients with continuous decrease in capillary density have a significantly higher incidence of multiple organ failure, which can provide important signals for clinical risk warning.

6. CHALLENGES AND FUTURE PROSPECTS IN CLINICAL APPLICATIONS

At present, the clinical application of tissue perfusion and microcirculation monitoring technology still faces many challenges: firstly, some invasive monitoring technologies have operational risks, which limit their application in coagulation dysfunction and elderly patients; Secondly, the accuracy of Non-invasive Monitoring Technology is influenced by various factors, and the results should be interpreted with caution in special populations [9]; Thirdly, there is a significant difference in equipment costs, and some advanced technologies (such as SDF) are difficult to popularize in primary hospitals, resulting in uneven distribution of medical resources; In addition, there is a lack of unified interpretation standards for results among different monitoring technologies, and clinical doctors have insufficient understanding of multi-parameter joint evaluation, which can lead to single indicator dependence and further affect the accuracy of technology application. Clinical research shows that about 35% of critical care physicians have interpretation bias in monitoring indicators during actual diagnosis and treatment, indirectly leading to delayed or biased treatment decisions. This interpretation bias not only affects the accuracy of treatment plans, but may also increase patients' medical burden and prognostic risks, especially in primary care facilities.

In the future, the development direction of monitoring technology will focus on minimally invasive, intelligent, and multi-parameter integration. On the one hand, reducing the trauma of invasive operations through technological innovation, developing more accurate and stable non-invasive monitoring equipment, and improving the applicability to special populations; On the other hand, utilizing artificial intelligence algorithms to integrate multidimensional monitoring data, constructing disease assessment and prognosis prediction models, and achieving intelligent optimization of treatment plans. At the same time, combining wearable device technology to achieve continuous dynamic monitoring provides the possibility for evaluating the perfusion status of critically ill patients during transportation and home rehabilitation outside the hospital; Promote interdisciplinary collaboration between engineering technology and critical care medicine, optimize the clinical adaptability of monitoring equipment, strengthen equipment configuration and personnel training in grassroots hospitals, promote standardized monitoring processes, effectively narrow the diagnosis and treatment gap between different levels of medical institutions, and improve the homogenization level of critical care patient management. This will help comprehensively improve the overall quality of critical care patient management [10].

7. CONCLUSION

The technology of tissue perfusion and microcirculation monitoring is the core means of managing critically ill patients. Its principle is based on the physiological and pathological mechanisms of the body, and objective indicators are obtained through invasive or non-invasive methods, providing scientific basis for disease assessment, treatment guidance, and prognosis judgment. It is also a key support for promoting the transformation of critical care medicine from empirical diagnosis and treatment to precise and personalized diagnosis and treatment mode. The clinical value of this technology is not only reflected in the critical care of ICU patients, but also throughout the entire cycle of emergency transportation, postoperative monitoring, and rehabilitation follow-up. By dynamically tracking changes in perfusion status, early warning and continuous intervention of severe risk can be achieved. Clinical practice has shown that the rational use of monitoring technology can significantly improve the accuracy of treatment for critically ill patients, reduce mortality and complication rates, and promote standardized monitoring processes and the construction of interdisciplinary collaboration mechanisms, which can further narrow the diagnosis and treatment gap between different levels of medical institutions and improve the level of medical service homogenization. Although current technological applications still face challenges such as operational risks, equipment costs, and interpretation capabilities, and the collaborative application mechanism of different monitoring technologies is not yet perfect, there is a lack of unified evidence-based support for monitoring schemes for special severe subtypes (such as immunodeficiency combined with septic shock). However, with the development and promotion of minimally invasive and intelligent technologies, tissue perfusion and microcirculation monitoring will play a greater role in the field of critical care medicine. In the future, it is necessary to further strengthen technological research and clinical studies, improve monitoring processes and interpretation standards, enhance equipment configuration and personnel training in primary healthcare institutions, promote the deep integration of multi-parameter monitoring data with electronic medical records and multiple organ function evaluation indicators, accelerate the clinical implementation of standardized guidelines, strengthen international academic cooperation and experience sharing, continuously optimize diagnosis and treatment strategies, provide stronger support for improving the short-term treatment effectiveness and long-term prognosis of critically ill patients, and help promote the high-quality development of the discipline of critical care medicine.

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